THE PENMAN-MONTEITH METHOD[1]

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INTRODUCTION

The Penman-Monteith method refers to the use of an equation for computing water evaporation from vegetated surfaces. It was proposed and developed by John Monteith in his seminal paper (Monteith, 1965) in which he illustrated its thermodynamic basis with a psychometric chart (a graph of vapor pressure at various relative saturations versus air temperature at a known air pressure). Monteith's derivation was built upon that of Howard Penman (Penman, 1948) in the now well-known combination equation (so named based on its "combination" of an energy balance and an aerodynamic formula) given as

$$\lambda E = \frac{[\Delta (R_n - G)] + (\gamma \, \lambda \, E_a)}{(\Delta + \gamma)} \qquad \ldots[1]$$

where λE is the evaporative latent heat flux in MJ m^{-2} d^{-1}, λ is the latent heat of vaporization in MJ kg^{-1} [λ = 2.45 MJ kg^{-1} at a temperature of 20ºC and taken as a constant for most purposes], Δ is the slope of the saturated vapor pressure curve [$\partial e^o/\partial T$, where e^o is saturated vapor pressure in kPa and T is the temperature in ºC, usually taken as the daily mean air temperature], R_n is net radiation flux in MJ m^{-2} d^{-1}, G is sensible heat flux into the soil in MJ m^{-2} d^{-1}, γ is the psychrometric constant in kPa $ºC^{-1}$ [~0.066 kPa $ºC^{-1}$ but proportional to barometric pressure relative to standard atmospheric pressure (101.3 kPa); e.g., at ~1,000 m elevation above sea level, γ is approximately 0.059 kPa $°C^{-1}$], and E_a is the vapor transport flux in mm d^{-1} [1.0 mm d^{-1} ≈ 1.0 kg m^{-2} d^{-1}]. Theoretically, Δ equals $(e_s^o - e_a^o) / (T_s - T_a)$, where e^o is the saturated vapor pressure in kPa, T is temperature in ºC, and the subscript "s" represent the vegetated surface and "a" represents the air (at some reference height above the ground). In addition, eqn. 1 applies only to cases where e_s^o is the saturated vapor pressure (e^o) at the surface temperature (T_s) [i.e., $e_s^o = e^o(T_s)$] (Van Bavel, 1966).

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Penman (1948) defined E_a empirically as

$$E_a = W_f \ (e^o - e_a) \qquad \text{...[2]}$$

where E_a is in mm d^{-1}, W_f is called a wind function in mm d^{-1} kPa^{-1} [typically expressed as a linear function of wind speed in m s^{-1} (U_z) at the reference height (z) above the ground], e^o is the saturated vapor pressure in kPa at mean air temperature, and e_a is mean ambient vapor pressure in kPa at the reference height above ground [e_a = RH e^o, where RH is mean relative humidity as a fraction; conceptually, e_a should equal the saturated vapor pressure at the daily mean dew point temperature]. The wind function, W_f, is typically expressed as a linear function of wind speed [e.g., a + b (U_z)]. Penman (1948) derived a curved W_f function [$a_1 U_z^{b1}$] but found a linear function was adequate. Penman noted in his 1948 paper one of the experimental problems needing a solution was the reliable estimation of the daily mean dew point temperature. This problem has led to current differences in using Penman's equation and has resulted in myriad different versions of a "modified Penman equation" with varying wind functions and methods for estimating mean daily vapor pressure deficit ($e^o - e_a$) (Jensen et al., 1990).

THE PENMAN EQUATION

It is critical to build the Penman-Monteith equation first on an understanding of the Penman equation and its subtleties. Penman (1948) defined E as open water evaporation. He expressed bare-, wet-soil evaporation or grass evaporation, E_o, (we now call this evapotranspiration, especially in the U.S.) as fractions of open water evaporation (E_w) [i.e., E_o = f E_w, where f is expressed as a fraction]. He estimated R_n by using albedo (short-wave irradiance reflectance) and emissivity (long-wave radiation emission factor) for water in eqn. 1. He derived and used W_f functions for an open water surface. The "f" values he measured typically varied from about 0.5-0.6 in winter to near 0.8-1.0 in summer. Grass evaporation "f" values were slightly larger than "f" values for bare soil with a water table near the surface (120 to 400 mm beneath the soil surface). For historical reference to those with inquisitive minds on experimental methods, the lysimeters Penman used in 1944 and 1945 were constructed in 1924 (and not by him) to allow time for the soil structure to be "realistic"; and his site, although well described in detail with complete drawings and one photograph in his paper, would seem inadequate today (Monteith, 1985). In a later hydrology manual (Penman, 1963), he determined the "two-stage process" using the "f" approach wasn't needed and computed "potential evaporation" (E_o) from a natural surface using the W_f and R_n and G for that surface. He defined potential evaporation as evaporation from "*a fresh green crop, of about the same color as grass, completely shading the ground, of fairly uniform height, and never short of water*" (Penman, 1956).

The Penman equation, therefore, only required routine weather observations (although some measurements like wind speed and cloud cover were not available everywhere) from a single level or height above ground. But the theory was rather advanced for its time. Without computers to perform the tedious computations, most engineers continued to rely on simpler evapotranspiration (ET) estimation methods such as the Blaney-

Criddle, Thornthwaite, or Jensen-Haise (Jensen et al., 1974). One of the earliest uses of the Penman equation in the U.S. was by Van Bavel (1956) for irrigation scheduling. Another advance to aid the use of the Penman equation was a wider acceptance and familiarity with metric units or the S.I. unit system that greatly streamlined the cumbersome original English units used in 1948.

TERMINOLOGY AND WHY WE'RE ALL CONFUSED

John Monteith, in a keynote address in 1985, elaborated that "*because Penman got the physics right, his formula has provided a basis for many theoretical and experimental studies*" [on p. 4 of Monteith (1985)], and he elaborated in an Appendix to his paper [on p. 12] why the term <u>evapotranspiration</u> was "*unnecessary*" and its component terms (evaporation and transpiration) "*strictly congruous*." Despite these misgivings from Monteith, the term <u>evapotranspiration</u> is too ingrained in U.S. literature and hydrologic and irrigation sciences and engineering as well as laws to move back to a more correct term, <u>evaporation</u>. Furthermore, the terms "potential evaporation" or "potential evapotranspiration" have been replaced by the term "<u>reference evapotranspiration</u>" (Doorenbos and Pruitt, 1975, 1977; Wright, 1982; Burman et al., 1990; and Burman et al., 1983) in current engineering usage (Jensen et al., 1990) and defined as "*the rate at which water, if available, would be removed from the soil and plant surface of a specific crop, arbitrarily called a reference crop*." Although any crop could be a reference crop, clipped grass (~0.12 m tall) or alfalfa (~0.5 m tall) have been the most widely used reference crop definitions (Jensen et al., 1990).

THE "MORE" THEORETICAL PENMAN EQUATION

The aerodynamic evaporative term, E_a, of Penman was expressed by several (Businger, 1956; Penman and Long, 1960; Van Bavel, 1966) using a theoretical adiabatic wind profile equation to define the momentum surface aerodynamic resistance (r_a). E_a is then defined as follows (for a 24-hr period)

$$E_a = \frac{\frac{\varepsilon \rho_a}{P} 86{,}400\,(e^o - e_a)}{r_a} \qquad \ldots[3]$$

where ε is the mole fraction of water in air [0.622], P is barometric pressure in kPa, the constant "86,400" is a unit conversion for seconds per day, and r_a is defined as

$$r_a = \frac{\left[ln\left(\frac{(z - d)}{z_o} \right) \right]^2}{k^2\, U_z} \qquad \ldots[4]$$

where r_a has units of s m^{-1}, z is the wind speed measurement height above ground in m [typically 2-3 m], d is the zero-plane displacement height in m [~2/3 of the reference crop height], z_o is the reference crop momentum aerodynamic surface roughness length in m

[~1/10 of the reference crop height], k is the von Karman constant [0.41], and U_z is the wind speed in m s^{-1} at the measurement height z above the ground. In practice, z_{om} values, as used in eqn. 4, have been artificially reduced by a factor of 10 [~1/100 of reference crop height] to obtain reasonable E_o values (Jensen, 1974). Eqn. 3, although theoretically attractive, has been demonstrated to often overestimate E_o in windy, dry climatic regimes (Rosenberg, 1969). Equation 1, as noted correctly by Van Bavel (1966), is a rate equation that should be applied using short-term weather data (i.e., hourly data), then integrated over the whole day. But the short term accuracy of predicting R_n (daytime albedo changes with season and solar elevation angle) and G (more important on an hour than a day) correctly often overshadowed the advantages of the improved accuracy in short-term E_a precision obtained through improved characterization of diel vapor pressure deficit or wind effects. Van Bavel (1966) indicated the accuracy of eqn. 1 for a day with daily weather parameters was a coincidence rather than a result from Penman's theory.

THE PRIMROSE PATH – THE "MODIFIED" PENMAN EQUATION

In summary for the Penman combination equation, users must be careful in defining the empirical wind function (or even the theoretical one – W_f), in how the daily vapor pressure deficit is computed and in particular how mean daily dew point temperature is estimated, how R_n and G are estimated, and how the many parameters affected by temperature, elevation, or latitude/longitude are computed. Jensen et al. (1990), Allen et al. (1994), and Allen et al. (1998) provide consistent equations for estimating R_n and G and the many parameters in the Penman equation. Because of the ease of creating a systematic bias in computing E_o with various procedures, especially when unspecified "modifications" are thrown in, one must utilize a fair skepticism despite the underlying fundamentally strong theoretical architecture of the Penman equation itself. The most widely used and successful "modified" Penman equation has been the <u>Penman-Wright</u> equation (Wright, 1982) for alfalfa reference evapotranspiration [note hereafter, we'll use ET_r for alfalfa or tall reference crops and ET_o for clipped grass or short reference crops]. Although we are using the name the <u>Penman-Wright</u> equation to highlight the developments and improvements from Jim Wright, this equation is more widely known as the Kimberly Penman equation (Jensen et al., 1990). In addition, weather data quality must be emphasized along with careful instrument maintenance and judicious weather station siting to obtain reliable, reproducible results from any equation.

THE PENMAN-MONTEITH EQUATION FRAMEWORK – INCLUDING THE SURFACE RESISTANCE

In the original Penman equation, the bulk surface resistance from the soil/crop was embodied in the wind function and not explicitly defined. Later aerodynamic forms of the Penman's E_a (i.e., eqns. 3-4) explicitly ignored the surface resistance (this partly explains why experience indicated z_o values had to be reduced so much to obtain "reasonable E_o rates). However, transpiration occurs from evaporation within the leaf substomatal cavity regulated by the leaf stomatal resistance (r_l) comprised by the parallel resistances (geometric average) of the adaxial side (top) and abaxial side (bottom) of the leaf. Plant physiologists consider stomatal resistance to be regulated through photosynthesis (internal CO_2 concentration maintenance) affected by solar irradiance. There is evidence of vapor pressure deficit feedbacks into stomatal regulation. These approaches are better applied on short time intervals (e.g., hourly or shorter intervals); however, for daily intervals simpler, approaches based on canopy leaf area index (LAI) have proven reliable. Allen et al. (1989) developed equations to estimate bulk surface resistance to water flux based on the crop height of grass or alfalfa in terms of the estimated crop LAI given as

$$LAI = 24\, h_c \qquad \textit{clipped grass with } h_c < 0.15\, m \qquad \ldots[5]$$

where h_c is the grass height in m. For nonclipped grass or alfalfa, they proposed

$$LAI = 1.5\, ln\,(h_c) + 5.5 \qquad \ldots[6]$$

with reference crop surface resistance (r_s) estimated as

$$r_s = \frac{100}{(0.5\, LAI)} \qquad \ldots[7]$$

For standard reference height crops of grass (h_c = 0.12 m) and alfalfa (h_c = 0.5 m), resulting r_s values are 70 s m^{-1} and 45 s m^{-1}, respectively.

THE PENMAN-MONTEITH EQUATION

Various derivations of the Penman equation included a bulk surface resistance term (Penman, 1953; Covey, 1959; Rijtema, 1965; and Monteith, 1965). The resulting equation is now called the Penman-Monteith equation, which may be expressed for daily values as

$$\lambda ET_o = \frac{\Delta\,(R_n - G) + \dfrac{86{,}400\, \rho_a C_P \left(e_s{}^o - e_a\right)}{r_{av}}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_{av}}\right)} \qquad \ldots[8]$$

where ρ_a is air density in kg m^{-3}, C_p is specific heat of dry air [~1.013 x 10^{-3} MJ kg^{-1} $°C^{-1}$], $e_s{}^o$ is mean saturated vapor pressure in kPa computed as the mean e^o at the daily minimum and maximum air temperature in ºC, r_{av} is the bulk surface aerodynamic resistance for water vapor in s m^{-1}, e_a is the mean daily ambient vapor pressure in kPa, and r_s is the canopy surface resistance in s m^{-1}. The Penman-Monteith equation represents the evaporating surface as a single "big leaf" (Raupach and Finnigan, 1988) with two parameters – one of which is determined by the atmospheric physics (r_{av}) influenced only slightly by the crop canopy architecture while the other one (r_s) depends on the biological behavior of the crop canopy surface and is related to both crop specific parameters (light attenuation, leaf stomatal resistances, etc.) and environmental parameters (irradiance, vapor pressure deficit, etc.). The water vapor aerodynamic resistance can be estimated following (Allen et al, 1989; and Jensen et al., 1990) as

$$r_{av} = \frac{\ln\left[\frac{(z_w - d)}{z_{om}}\right]\ln\left[\frac{(z_r - d)}{z_{ov}}\right]}{k^2 \, \mathrm{U_z}} \qquad \text{...[9]}$$

where z_w is the wind speed measurement height in m, z_{om} is the momentum roughness length in m, z_r is the relative humidity measurement height in m, and z_{ov} is the vapor roughness length in m. The crop canopy aerodynamic parameters are estimated as follows

$$\begin{aligned} d &= (2/3)h_c \\ z_{om} &= 0.123\, h_c \\ z_{ov} &= 0.1\, z_{om} \end{aligned} \qquad \text{...[10, 11, \& 12]}$$

Eqn. 8 is referenced here as the ASCE Penman-Monteith equation with all parameters computed as outlined by Jensen et al. (1990).

FAO-56 PENMAN-MONTEITH EQUATION

Allen et al. (1998) simplified eqn. 8 by utilizing some assumed constant parameters for a clipped grass reference crop that is 0.12-m tall in an extensive report for the Food and Agriculture Organization of the United Nations (FAO-56 Paper). They assumed the definition drafted by an FAO Expert Consultation Panel (Smith et al., 1992) for the reference crop as "*a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23*." By further assuming a constant for λ and simplifying the air density term (ρ_a), they derived the FAO-56 Penman-Monteith equation using the fixed bulk surface resistance (70 s m^{-1}) and the vapor aerodynamic resistance simplified to an inverse function of wind speed ($r_{av} = 208 / U_z$), as

$$ET_o = \frac{0.408\, \Delta (R_n - G) + \gamma \frac{900}{T + 273} U_2 \left(e^o - e_a\right)}{\Delta + \gamma (1 + 0.34 U_2)} \qquad \text{...[13]}$$

where ET_o is the hypothetical reference crop evapotranspiration rate in mm d^{-1}, T is mean air temperature in °C, and U_2 is wind speed in m s^{-1} at 2 m above the ground [and RH or dew point and air temperature are assumed to be measured at 2 m above the ground, also]. Allen et al. (1998) provide procedures for estimating all the parameters consistent with Allen et al. (1989) and Jensen et al. (1990) for a grass reference crop with the defined hypothetical characteristics. The data required are the daily solar irradiance, daily maximum and minimum air temperature, mean daily dew point temperature (or daily maximum and minimum RH), mean daily wind speed at 2-m elevation and the site elevation, latitude, and longitude. Eqn. 13 can be applied using hourly data if the constant value "900" is divided by 24 for the hours in a day and the R_n and G terms are expressed as MJ m^{-2} hr^{-1}. Allen et al. (1994) used eqn. 13 on an hourly basis in Utah with success, particularly if they corrected the aerodynamic resistance for atmospheric stability (see Brutsaert, 1982) even with a constant r_s (~70 s m^{-1}) throughout the day and night.

Both the FAO-56 book (Allen et al., 1998) and the ASCE manual (Jensen et al., 1990) were significant milestones in developing a consistent methodology for estimating R_n and G as well as the other parameters involved in eqns. 8 and 13.

THE ASCE-EWRI STANDARDIZED PENMAN-MONTEITH EQUATION

In 1999, the ASCE Environmental and Water Resources Institute Evapotranspiration in Irrigation and Hydrology Committee was asked by the Irrigation Association to propose one standardized equation and set of procedures for estimating the parameters to gain consistency and wider acceptance of ET models. This committee formed a Task Committee chaired by Ivan Walter (Walter et al., 2002) that held a series of meetings and vigorous debates on means to standardize the reference ET computations using the Penman-Monteith equation. The Task Committee built on the FAO-56 (Allen et al., 1998) frame to develop reference ET computations that could be based on the latest engineering and scientific principles and that could be defended and that would be accurate and applicable across diverse climates. The committee had diverse geographic representation and diverse disciplines represented. The principle outcome was that <u>TWO</u> equations (one for a short crop named ET_{os} and another for a taller crop named ET_{rs}) were developed for daily (24 hr) and hourly (or even shorter) time periods. Allen et al. (2000) outlined the purpose and needs for a standardized reference ET methodology.

The ASCE-EWRI standardized reference ET equation based on the FAO-56 Penman-Monteith equation (eqn. 13) for a hypothetical crop with typical characteristics given in Table 1 (Walter et al., 2002) is given as

$$ET_{sz} = \frac{0.408\,\Delta(R_n - G) + \gamma \dfrac{C_n}{T+273} U_2 \left(e_s{}^o - e_a\right)}{\Delta + \gamma\left(1 + C_d\ U_2\right)} \qquad \ldots[14]$$

where ET_{sz} is the standardized reference crop evapotranspiration for a short reference crop (ET_{os}) or a tall reference crop (ET_{rs}) in units based on the time step of mm d^{-1} for a 24-hr day or mm hr^{-1} for an hourly time step [time units on R_n and G match those for the evapotranspiration rates], C_n is the numerator constant for the reference crop type and time step, and C_d is the denominator constant for the reference crop type and time step (see Table 2 for values of C_n and C_d). The ASCE-EWRI Standardized reference ET manual (Walter et al., 2002) provides a more thorough derivation of procedures for estimating R_n and G for both reference crops on hourly time steps beyond the FAO-56 book (Allen et al., 1998). The ASCE-EWRI manual also addresses important issues on

Table 1. Reference crop characteristics and Penman-Monteith equation constants for the standardized ASCE-EWRI equation.

Term	ET_{os} (short reference crop)	ET_{rs} (tall reference crop)
Vegetation height, h_c	0.12 m	0.5 m
Height of wind speed measurement, z_w	2 m	2 m
Height of air temperature and RH measurements, z_r	1.5 – 2.5 m	1.5 – 2.5 m
Zero-plane displacement height, d	0.08 m	0.08 m§
Latent heat of vaporization, λ	2.45 MJ kg^{-1}	2.45 MJ kg^{-1}
Surface resistance, r_s, daily	70 s m^{-1}	45 s m^{-1}
Surface resistance, r_s, daytime	50 s m^{-1}	30 s m^{-1}
Surface resistance, r_s, nighttime	200 s m^{-1}	200 s m^{-1}
R_n cutoff for daytime	> 0 MJ m^{-2} hr^{-1}	> 0 MJ m^{-2} hr^{-1}
R_n cutoff for nighttime	≤ 0 MJ m^{-2} hr^{-1}	≤ 0 MJ m^{-2} hr^{-1}

§ The zero-plane displacement height for ET_{rs} assumes U_2 is measured over clipped grass.

Table 2. Values of C_n and C_d for eqn. 14.

Calculation Time step	Short Reference Crop, ET_{os}		Tall Reference Crop, ET_{rs}		Units for ET_{os}, ET_{rs}	Units for R_n and G
	C_n	C_d	C_n	C_d		
Daily	900	0.34	1600	0.38	mm d^{-1}	MJ m^{-2} d^{-1}
Hourly, daytime	37	0.24	66	0.25	mm hr^{-1}	MJ m^{-2} hr^{-1}
Hourly, nighttime	37	0.96	66	1.7	mm hr^{-1}	MJ m^{-2} hr^{-1}

weather data quality assurance and estimating missing climatic data needed in the Penman-Monteith equation.

PERFORMANCE – IN THE "REAL" WORLD

We used a few days of data measured at Bushland, Texas (35º 11' N lat.; 102º 06' W long.; 1,170 m elev. above MSL) during a period of fairly extreme advection for irrigated alfalfa in 1998 to illustrate the equation performance in an extreme and challenging environment. The period was June 13-22 [DOY 164-173] during a regional drought (that is still continuing). The alfalfa was in its second cutting cycle and swathed on DOY 174 [June 23rd]. Its height was 0.55 m on June 17th with a LAI (leaf area index) between 2.4 to 2.6 m^2 m^{-2}. On June 23rd, it had a height of 0.62 m and a LAI of 3.1 m^2 m^{-2}.

Interestingly for information only, eqns. 6 & 7 computed a bulk surface resistance just a little less than the standardized hypothetical value of 45 s m^{-1}, but the computed LAI from eqn. 5 over-predicted considerably the measured LAI during this period. All computations used the hypothetical standardized surface resistance (r_s) values (Table 1). Evapotranspiration from alfalfa was measured with two large, precise, monolithic weighing lysimeters (each 3 m by 3 m by 2.3 m deep) each situated in the center of 5 ha fields irrigated with a lateral-move sprinkler system that supplied adequate water for near maximum daily ET during this period (Marek et al., 1988). Weather data were measured adjacent to the alfalfa fields in an irrigated grass weather station. Solar irradiance, air temperature and relative humidity (in a cotton belt shelter), 2-m wind speed, and barometric pressure data were used to compute reference evapotranspiration from the nearby alfalfa fields. The weather station was irrigated (via SDI irrigation) and routinely mowed to maintain a grass height between 0.10 to 0.15 m. Other details regarding the site, instruments, and procedures can be found in Howell et al. (1997).

We computed alfalfa reference evapotranspiration (or tall crop reference ET, ET_{rs}) by the Penman-Wright equation (Wright, 1982) [known also as the Kimberly Penman equation], by the ASCE Penman-Monteith equation (Jensen et al., 1990), and by the ASCE-EWRI Standardized Reference equation (Walter et al., 2002) using daily (24-hr) weather data. The ASCE Penman-Monteith procedure used all parameters computed and corrected along with measured barometric pressure data from the weather station. The other daily equations used computed barometric pressure based on the elevation. For comparison, we computed the grass reference evapotranspiration (short reference crop, ET_{os}) and the tall crop standardized reference evapotranspiration using half-hourly weather data (again from the clipped grass, irrigated weather station). The results for these days are summarized in Table 3.

The two weighing lysimeter measurements indicated a 3.2% greater ET for the south lysimeter with the shorter fetch (~100 m fetch for the south lysimeter and ~300 m fetch for the north lysimeter for prevailing winds from the SW direction across dryland crops and fallow fields extending over 1.0 km). Other factors could influence the lysimeter differences besides fetch. The range in lysimeter measured ET was from 6.9 to 17.8 mm d^{-1} during this period. The mean lysimeter ET for these 10 days was 12.9 mm d^{-1}. The daily Penman-Monteith equations (the ASCE and the ASCE-EWRI Standardized versions) agreed together well. The mean back computed daily bulk surface resistance to match the lysimeter ET rate during these days was 45.6 s m^{-1}, which is insignificantly greater than the hypothetical value of 45 s m^{-1} for a tall reference crop. The ratio of the ASCE-EWRI tall crop reference ET to the short reference crop ET was 1.43, indicating the advective effects in this environment during this period and considerably greater than the mean of 1.27 reported by Itenfisu et al. (2003) for various sites across the U.S.

For the six days without irrigations (where the lysimeter water balance should be practically without error), the ASCE-EWRI Standardized equation computed with half-hourly weather data and integrated for the day had the lowest bias (regression intercept was lowest and slope was nearest to 1.0) and greatest coefficient of determination (r^2). On average, the Penman-Wright equation had the closest (0.6% difference) match (in average and sum) with the measured alfalfa ET on these days, but it had the highest bias and lowest slope (agreement). Both the ASCE-EWRI Standardized reference ET (4.2% difference) and the ASCE Penman-Monteith version slightly over predicted (8.0% difference) measured ET on average for the 10 days, both were less biased than the Penman-Wright equation on these days with regression slopes nearer to 1.0 (0.71 and 0.74, respectively) . The ASCE-EWRI Standardized reference ET computed using half-hourly weather inputs under predicted (-2.7% difference) measured ET on average, but it was the least biased and highest correlated to the measurements during this advective period. Itenfisu et al. (2003) also reported a near perfect agreement for the summed hourly ASCE-EWRI Standardized equation compared with the daily ASCE-EWRI Standardized equation for Bushland for two years including 1998.

Table 3. Measured and computed reference evapotranspiration at Bushland, Texas in 1998 during a drought with advection events.

Date	DOY	ASCE ET_{rs} mm d^{-1}	ASCE EWRI ET_{rs} mm d^{-1}	ASCE EWRI ET_{rs}§ Mm d^{-1}	ASCE EWRI ET_{os} Mm d^{-1}	Penman -Wright ET_r mm d^{-1}	Lys. ET (NE) mm d^{-1}	Lys. ET (SE) mm d^{-1}
Jun 13	164	16.7	16.0	16.9	10.8	15.4	17.5	17.8
Jun 14	165	11.8	11.0	10.2	8.0	11.7	9.8	10.0
Jun 15†	166	9.2	9.0	7.9	6.6	9.6	6.9	6.9
Jun 16	167	15.9	15.8	14.7	10.7	14.5	15.2	16.1
Jun 17†	168	18.9	17.8	16.0	11.8	17.3	15.5	16.0
Jun 18†	169	12.1	11.0	11.1	8.1	12.2	12.0	12.0
Jun 19†	170	13.6	12.9	12.4	9.1	13.0	11.2	12.1
Jun 20	171	14.2	13.5	13.5	9.4	13.5	15.9	16.2
Jun 21	172	11.2	11.4	9.6	8.3	10.7	8.9	9.4
Jun 22	173	15.6	15.9	13.1	10.9	13.7	13.9	14.4
Mean		13.9	13.4	12.5	9.4	13.2	12.7	13.1
Sum		139.3	134.3	125.3	93.6	131.7	126.7	130.9

§ Based on sum of 48 half-hour computed values per day.
†Days with irrigations.

Figure 1 illustrates the measured and computed ASCE-EWRI standardized reference ET on June 13th and the following day using weather data measured at each lysimeter. The first day experienced strong regional advection from high winds and low humidity. The second day was more typical of near normal weather. The ASCE-EWRI Standardized reference ET computed with half-hourly weather data from the weather station was16.9 mm d^{-1} (Table 3) on the first day with lysimeter measurements summing to 17.7 mm d^{-1}(error of -2.7% if one assumes the measured alfalfa ET was correct). On the next day, the ASCE-EWRI Standardized half-hourly computed tall crop reference ET using the weather station data almost exactly matched the lysimeter measurements (computed reference ET_{rs} was 10.2 mm d^{-1} while the lysimeter measurements averaged 9.9 mm d^{-1} on June 14th) (error of 3% if one assumes the measured alfalfa ET was correct).

The crop parameters used in any hypothetical reference crop ET equation can be expected to, at best, only approximate "real world" conditions that can vary between seasons, temporarily during the year, between varieties, etc. It is highly encouraging that we observed such small differences [we hesitate to say error because we are never absolutely sure which is in error – the model or the measurements]. It is also heartening to be able to observe such good agreement in the model from Idaho (Penman-Wright equation) that has never before been tested under such highly advective conditions. At the same time, we noted the Penman-Wright equation had a higher bias on these days and one of the poorest correlations with the measured ET. Previous calculations have

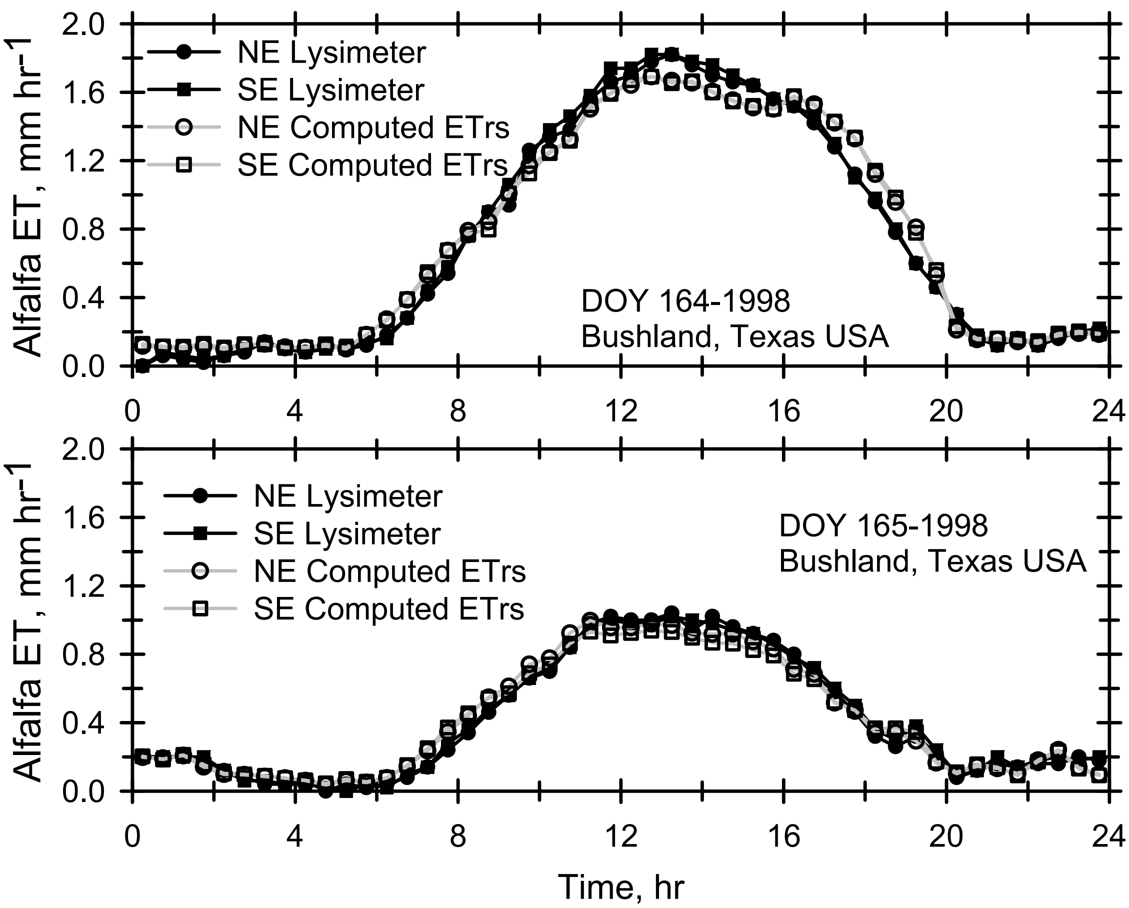

Figure 1. Measured and computed reference evapotranspiration of alfalfa [a tall reference crop] during two days in June of 1988. Day 164, June 13, experienced strong advection from high winds and low humidity while the next day, DOY 165 – June 14th, had a more typical environment. Lysimeter ET averaged 17.7 mm d^{-1} on DOY 164 and 9.9 mm d^{-1} the following day. [Unpublished data from the authors].

indicated a slightly lower daytime bulk surface resistance (r_s) for alfalfa at Bushland (Todd et al., 2000) under well-watered conditions than the hypothetical daytime resistance of 30 s m^{-1} (Table 1) recommended by the ASCE-EWRI Standardized reference ET procedures. One of the goals of the ASCE-EWRI Standardized equation

(Allen et al., 2000; Walter et al., 2002) is to reasonably match reference ET measurement, not to necessarily model a specific situation that might differ somewhat from the “standardized” reference crop characteristics. In this respect, the ASCE-EWRI Standardized ET equation for a tall reference crop would be viewed as successful under this short period test but extreme environment.

SUMMARY

The Penman-Monteith equation is based on the physics from the original Penman combination equation that has proven effective if applied correctly with high quality weather data. The ASCE-EWRI Standardized reference ET equation appears to meet the goals established for its creation. Its hypothetical crop parameters, for a taller and aerodynamically rougher crop like alfalfa anyway, appear reasonable for computations of ET for a well-watered crop even under strong regional advection.

The ASCE-EWRI Standardized reference ET equation needs additional testing and evaluation across diverse environments, but evaluations to date are encouraging.

ACKNOWLEDGEMENTS

We recognize the efforts of Karen Copeland, Soil Scientist, with USDA-ARS at the Conservation & Production Research Laboratory, who processed these data and assisted with the calculations. Many other technicians in the Soil and Water Management Research Unit at the laboratory are responsible for the care, operation, and maintenance of the weighing lysimeters and the weather station facilities.

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